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RESEARCH MEMORANDUM

EFFECT OF INLET-AIR TEMPERATURE ON PERFORMANCE OF A 16-INCH RAM-JET COMBUSTOR

By A. J. Cervenka, E. E. Dangle, and Robert Friedman

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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RESEARCH MEMORANDUM

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SUMMARY

The effect of inlet-air temperature on the combustion efficiency of a 16-inch ram-jet engine was determined in a connected-pipe installation. The engine was operated over a range of fuel-air ratio with several different combustor configurations and two fuel types.

Combustion efficiency was found to be as much as 35 percentage points lower at an inlet-air temperature of 160° F than at 600° F. The variation in efficiency was a function of fuel-air ratio and combustor design. With flame-holder designs in which the local fuel-air ratio was maintained near stoichiometric in the burning zone, or at over-all ratios near stoichiometric, the temperature effect was slight. When the local fuel-air ratio varied appreciably from stoichiometric, a greater effect was found. These findings are in accordance with previous observations, discussed in a survey of literature, in which the effect of temperature was shown to diminish at the regions of high combustion efficiency.

The performance of a sloping-baffle flame holder at an inlet-air temperature of 160° F with gasoline fuel was about the same as with MIL-F-5624A grade JP-4 fuel at 600° F over a range of fuel-air ratio from 0.020 to 0.062.

INTRODUCTION

This investigation is part of a ram-jet combustor design program being conducted at the NACA Lewis laboratory. The objective of this program is the attainment of combustor design and design criteria that will permit stable and efficient ram-jet combustion over wide ranges of fuel-air ratio and combustor-inlet conditions.

The initial phases of this program reported in references 1 to 4 were conducted at a simulated flight Mach number of 2.9 and at a corresponding inlet-air temperature of 600° F. At this test condition, which is within the range of interest for long-range missile application, combustor designs were evolved that gave combustion efficiencies of 90 percent or greater over a fuel-air ratio range from 0.010 to 0.060.

There is, nevertheless, considerable interest in ram-jet applications at lower flight Mach numbers and at correspondingly lower inlet-air temperatures. Therefore, an investigation was undertaken to establish the quantitative effect of inlet-air temperature upon the performance of selected ram-jet combustor designs. The inlet-air temperatures investigated ranged from 160° to 600° F. Additional variables were introduced by the use of several combustor configurations and two fuel types.

Previous pertinent analytical and experimental work on the effect of inlet-air temperature on ram-jet combustor performance was reviewed, and the findings are discussed in relation to the experimental data presented herein. 3043

SYMBOLS

The following symbols are used in this report:

A_c	combustor maximum cross-sectional area, sq ft
A_F	flame front area, sq ft
E	activation energy, Btu/lb
e	base of natural logarithms
H	minimum spark-ignition energy, Btu
K_1, K_2, etc.	constants
N	fuel evaporated for gasoline-type fuel injected contrastream from a simple orifice-type nozzle, percent
n	constant
p_i	combustor-inlet static pressure, lb/sq ft abs
p_r	static pressure at beginning of reaction, lb/sq ft abs
p_0	static pressure at point of ignition, lb/sq ft abs
R	specific gas constant, Btu/lb/°R
T_i	combustor-inlet absolute temperature, °R
T_r	absolute temperature at beginning of reaction, °R

T_0 absolute temperature at point of ignition, °R

U_F fundamental flame velocity at standard conditions, usually 298° K, ft/sec

u_F flame velocity at combustor-inlet conditions, ft/sec

V_c inlet mixture velocity based upon maximum cross-sectional area of combustor, ft/sec

V_i combustor-inlet velocity, ft/sec

X fraction of original fuel-air mixture that reacts in a given period of time

η_b combustion efficiency, percent

η_{im} impulse efficiency, percent

ρ_u density of unburned gases, lb/cu ft

Φ functional notation

THEORETICAL BACKGROUND

The effect of inlet-air temperature upon the combustion process in a jet engine can be examined theoretically if a simplified model of the process is assumed. The actual combustion process consists of successive steps of vaporization of the fuel, mixing of fuel and air, and oxidation of the fuel-air mixture. Thus, a simplified combustion model can be set up by the assumption that one of these steps is sufficiently slow with respect to the others, so that the slow step would control the over-all combustion rate and hence govern the combustion efficiency. For example, in a model where vaporization is controlling, the over-all rate of combustion would be determined by the rate of evaporation of fuel. For this case, the influence of inlet temperature and other conditions upon evaporation rate is reported by reference 5 as the equation

$$\frac{N}{100-N} = K_1\left(\frac{T_i}{100}\right)^{4.4} \frac{V_i^{0.80}}{p_i^{1.2}} \tag{1}$$

Equation (1) shows the strong dependence of degree of evaporation upon temperature and the lesser influence of inlet pressure and velocity.

For a mixing-rate-controlling model, the effect of inlet temperature is not usually expressed explicitly; instead, a Reynolds number correlation is employed. In reference 6 a nearly linear relation between Reynolds number and eddy diffusivity, a mixing-rate parameter, is reported in the range of Reynolds number of interest in the ram-jet field. In the burning zone, flame area is also a function of Reynolds number (ref. 7).

The assumption of an oxidation-rate-controlling mechanism for the 3043
combustion process allows the use of several methods of expressing temperature relations. These methods involve the use of such parameters as minimum spark-ignition energies, flame speeds, and reactant concentrations. The effect of temperature and pressure upon minimum spark ignition is reported in reference 8. The data of reference 8 have been plotted and found to fit the equation

$$H = \frac{K_2}{T_0^3 p_0^2} \qquad (2)$$

The relation between temperature and a flame-speed parameter is shown in reference 9 to follow the form

$$u_F = K_3 + K_4 T_1^n \qquad (3)$$

The effect of temperature upon chemical reaction is given by the well-known Arrhenius equation. A specific form of this equation, derived for application to combustor studies, is shown in reference 10

$$\frac{X}{1-X} = K_5 \frac{p_r}{R^{1/2} T_r^{1/2}} e^{-E/RT_r} + K_6 \qquad (4)$$

EXPERIMENTAL BACKGROUND

The characterizing quantities discussed in the preceding paragraphs have all been suggested for possible use in combustion-efficiency correlations. Vaporization-controlling mechanisms have not been employed successfully in this respect, although measurements of the effect of fuel vaporization upon efficiency have been reported by many sources, such as references 2, 11, and 12. The experience of these investigators has been that vaporization rate is not controlling under the usual conditions of ram-jet-engine combustor operation.

For combustion mechanisms that assume oxidation-rate controls, several correlations of combustion efficiency have been proposed, each

being derived from one of the temperature-dependent parameters given in equations (2) to (4). Minimum spark-ignition energy is used in reference 13 to correlate efficiency of a turbojet combustor. The data are presented in the form of a plot of η_b as a function of p_i^2/H where η_b is combustion efficiency, p_i is combustor inlet static pressure, and H is minimum spark-ignition energy. An approximate formula may be written for the linear portion of the curve up to efficiencies of about 80 percent. This formula, with the temperature substitution for H
3043 from equation (2), is

$$\eta_b = \log\left(K_7 T_i^{4/3}\right) \tag{5}$$

Another correlation employing minimum spark-ignition energy is given by reference 14 in which impulse efficiency rather than combustion efficiency is employed as the performance criterion. A linear portion of the plot presented in reference 14 with temperature substituted for ignition energy from equation (2) may be represented by the relation

$$\eta_{im} = \log\left(K_8 T_i^{0.44}\right) \tag{6}$$

In references 7 and 15, a combination of mixing- and oxidation-controlling mechanisms is utilized. Combustion efficiency η_b is defined in terms of flame area (a mixing parameter) and flame speed (an oxidation parameter)

$$\eta_b = \frac{\rho_u A_F u_F}{\rho_u A_c V_c} \tag{7}$$

The flame area A_F was evaluated as a function of velocity, pressure, and temperature; and the flame speed u_F was expressed as a function of temperature. From these substitutions and experimental measurements upon vaporized stoichiometric fuel-air mixtures in a 5-inch ram-jet combustor, a correlation of combustion efficiency is established in the form

$$\eta_b = 7.0 \frac{p_i^{0.3} T_i}{V_i^{0.8}} \left(\frac{U_F}{1.4}\right)^{1.1} \tag{8}$$

This correlation holds up to efficiencies of 80 percent, above which the dependence of η_b upon the pressure-temperature-velocity parameter decreases sharply. The flame-speed factor allows equation (8) to be applied to different fuel types, exceptions being certain fuels such as carbon disulfide whose low ignition energy apparently causes combustion steps other than oxidation to be controlling (ref. 15).

The reaction-rate quantity given in equation (4) forms the basis of an efficiency correlation proposed in reference 10. In this correlation, combustion efficiency is defined in terms of the fraction of the total fuel consumed in the reaction time allowed by the inlet velocity and combustor length. The final correlation is given in the form of a function of $p_i T_i / V_i$, with turbojet performance data correlated according to the equation

$$\eta_b = \Phi\left(\frac{p_i T_i}{V_i}\right) \qquad (9)$$

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In this correlation the decreased effect of the inlet conditions upon combustion efficiency where the efficiency is greater than 80 or 85 percent is also noted. At efficiencies greater than 85 percent, the slope of the correlating curve is very gradual.

While of considerable interest, these combustion-efficiency correlations are not in themselves sufficient for prediction of efficiencies of actual ram-jet-engine combustors. The actual combustion process is far more complicated than indicated in the models set up for the correlations, and rarely can an actual combustor performance be identified as corresponding to these simplified concepts. Nevertheless, these correlations do serve a very useful purpose in indicating trends in the effect of inlet conditions and suitable ranges of operation with respect to high efficiency.

The most helpful experimental investigations for the purpose of combining experimental and analytical correlations of the effect of inlet variables, specifically temperature, upon combustion efficiency are those in which these variables in the test burners are studied independently. Early ram-jet work in this respect is that of reference 16, where the effect of inlet temperature, pressure, velocity, and combustion-chamber length upon combustion efficiency was studied in an 8-inch ram-jet combustor. The work presents plots confirming the hypotheses that the combustion efficiency is improved by increased temperature, pressure, combustor length, and by decreased inlet-air velocity.

The correlations of both references 7 and 10 indicate that combustion efficiency below values of 80 percent increases linearly with absolute inlet-air temperature. In reference 17, the effect of inlet-air temperature is shown for investigations carried out with both 5-inch and 20-inch combustors employing V-gutter and can-type flame holders. Data for homogeneous, prevaporized fuel injection show a linear effect of inlet temperature upon combustion efficiency. Data obtained with local liquid injection into the 20-inch V-gutter combustor, on the other hand, fail to obey a linear relation, presumably because evaporation rate governs the efficiency in this case. Other investigations of interest include those of reference 18 for a 20-inch ram jet, reference 12 for a

2-inch burner, and reference 19 for a 10-inch quarter-segment can. These studies show that the effect of temperature is felt most strongly at fuel-air ratios where the efficiency is low; thus, increasing inlet temperature broadens the range of fuel-air ratio at which high combustion efficiencies are obtained.

From the experience of these previous investigations, it may be concluded that if the combustor is operating at high efficiency near the combination of inlet conditions where the temperature effect becomes appreciable, a decrease in operating temperature will cause a marked drop in combustion efficiency. In contrast, if the combustor is operating at nearly the same high efficiency, but well above the critical value of inlet variables, a decrease in operating temperature will not affect the combustion efficiency.

APPARATUS

The 16-inch ram-jet engine and test installation for this investigation, shown in figure 1, were the same as described in reference 1.

Flame holders. - The two flame-holder configurations used were the sloping baffle and can shown in figures 2(a) and 2(b). Design details of these flame holders are given in references 3 and 4. The ratio of the cold-flow total-pressure drop across the flame holder to the dynamic pressure upstream of the flame holder was 1.5 for the can and 2.0 for the sloping baffle.

Fuel injectors. - The same fuel injectors were used with the sloping-baffle flame holder (configuration A, fig. 2(a)) and with the can-type configurations in which upstream injection was used (configurations B and C, figs. 2(b) and 2(c)). A mixture-control sleeve was used for configurations A and C to maintain a locally rich zone before the flame holders (ref. 1). The six primary spray nozzles, located so that the fuel spray would enter the control sleeve, were rated at 0.5 gallon per minute at a pressure differential of 100 pounds per square inch. The 16 nozzles that supplied secondary fuel, located so as to spray into the annulus outside of the control sleeve, were rated at 0.36 gallon per minute at the same pressure differential. Details of the nozzle arrangement used with the internal fuel-injection system in configuration D are given in figure 2(d).

Fuel. - The properties of the two fuels, MIL-F-5624A grade JP-4 and clear gasoline, are given in table I.

PROCEDURE

Operating conditions. - The ram-jet combustor was operated at the air mass flows, range of inlet pressure, and range of inlet velocity noted for the following inlet-air temperatures:

Inlet-air temperature, °F	600	480	300	160
Air mass flow, lb/sec	14.5	18	20.5	25
Inlet-air velocity, ft/sec	230-260	200-260	170-260	165-260
Inlet-air pressure, in. Hg abs	36-32	46-33	50-33	54-33

The inlet air was preheated by a gas-fired heat exchanger and was thus supplied to the test unit uncontaminated.

Combustion efficiency. - Combustion efficiencies were determined by a heat-balance system. Combustion efficiency is defined as the ratio of the enthalpy change of fuel, air, quench water, and engine cooling water to the heating value of the fuel input. At a given engine operating condition, the quench-water flow was adjusted to a value insuring quenching of the combustion products and complete vaporization of the water. Mixture temperatures of 600° to 900° F were maintained at the thermocouple station. Negligible heat loss from the ducting downstream of the water spray was assumed.

RESULTS AND DISCUSSION

Sloping Baffle - Configuration A

The combustor performance data obtained with the sloping-baffle flame holder (configuration A) over a range of inlet-air temperature from 160° to 600° F and with two fuels are shown in figure 3(a). Efficiencies of 90 percent or greater were obtained at all temperatures investigated in the fuel-air range from 0.030 to 0.062. Since inlet-air pressure and velocity varied appreciably with fuel-air ratio at the low inlet-temperature conditions, the effect of temperature on combustion efficiency is not clearly shown near stoichiometric conditions. In the fuel-air ratio range from 0.010 to 0.030, the effect of temperature became more pronounced, since the inlet conditions of pressure and velocity were more severe than at higher fuel-air ratios.

At a fuel-air ratio of 0.0155, combustion efficiency decreased from 93 to 60 percent when the air temperature was decreased from 600° to 160° F. This is almost a linear dependence of combustion efficiency with inlet absolute temperature. Thus, it appears that while the conditions of the runs above a fuel-air ratio of 0.030 are such that the inlet temperature has little effect upon efficiency, the inlet pressure and velocity at fuel-air ratios below 0.030 are sufficiently stringent to produce the greater temperature effect cited in references 7, 10, and 15.

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At the 160° F inlet conditions, a rich stable burning limit was encountered at a fuel-air ratio of 0.034 with JP-4 fuel. No limits were found with gasoline. A possible explanation for the rich limit was the impingement and collection of liquid fuel on the control sleeve and other surfaces upstream of the burning zone, resulting in an unfavorable vapor fuel-air mixture downstream of the baffle with the less volatile fuel. Combustion efficiencies with gasoline fuel at 160° F were approximately the same as with JP-4 at the 600° F condition over the fuel-air ratio range from 0.020 to 0.062.

Can-Type Combustor - Configuration B

In figure 3(b) is shown the effect of inlet-air temperature on the performance of a can-type combustor with upstream fuel injection (configuration B). The trend in combustion efficiency with inlet-air temperature was similar to the trend found with configuration A. At rich mixtures no significant temperature effect was found, whereas at lean fuel-air ratios efficiency increased considerably with increasing inlet-air temperature (20 percentage points at a fuel-air ratio of 0.025).

Stability limits were also improved with increased temperature. Lean blow-out occurred at a fuel-air ratio of 0.009 at 160° F, whereas no limits were found at 600° F.

Can-Type Combustor - Configuration C

The performance data obtained with the can-type flame holder, dual upstream injection, and control sleeve (configuration C) are shown in figure 3(c). Combustion efficiencies were 92 percent or greater at an inlet-air temperature of 600° F with proper selection of primary- and secondary-fuel flows. At lower temperatures, the efficiencies ranged from 80 to 90 percent, except for a limited region in the lean and rich fuel-air ratio ranges where values greater than 90 percent were obtained. A fuel-air ratio of approximately 0.025 apparently represents a stoichiometric mixture in the primary zone. At this fuel-air ratio and at an over-all fuel-air ratio near stoichiometric, very little temperature effect was found.

The effects of primary fuel-air ratio and fuel type with this configuration are shown in figure 4. These data indicate that in the transition region between primary alone and combined primary and secondary fuel injection (0.025 to 0.035) a primary fuel-air ratio of 0.025 gives best results for JP-4 fuel. For richer operation, the primary fuel-air ratio should be reduced to 0.014. A slight improvement with gasoline over JP-4 fuel was noted in the rich region.

Can-Type Combustor - Configuration D

The effect of inlet-air temperature on the performance of a can-type combustor with internal fuel injection is shown in figure 5. With this configuration, combustion efficiency was high at lean and low at rich mixtures for all the inlet temperature conditions investigated. 3043
At a fuel-air ratio of 0.020, a temperature increase from 160° to 600° F resulted in a combustion efficiency increase from 87 to 96 percent. The same temperature variation at richer conditions resulted in efficiency increases of 15 to 20 percentage points.

The effects of primary fuel flow and fuel type are shown in figure 6. Except for a slight advantage with primary fuel injection only at a fuel-air ratio of 0.020, no effects of primary fuel flow or fuel type were observed.

From the results of these tests, it appears that the effect of inlet-air temperature upon combustion efficiency is slight for flame-holder designs in which the local fuel-air ratio is maintained near stoichiometric in the burning zone, even though the over-all fuel-air ratio varied. On the other hand, with combustors in which the local fuel-air ratio varied appreciably from stoichiometric, either rich or lean, the effect of inlet temperature was more pronounced and approached the magnitude predicted by the correlations of references 7 and 10. Thus, it is seen that the favorable stoichiometric conditions correspond to the regions of small temperature effects, and the more severe off-stoichiometric conditions correspond to the regions of greater temperature effect.

SUMMARY OF RESULTS

The following results were obtained from an investigation of a 16-inch ram-jet engine with both can-type and sloping-baffle flame holders in a connected-pipe installation:

1. Combustion efficiency was found to be 0 to 35 percent lower at an inlet-air temperature of 160° F than at 600° F. The variation in efficiency levels was a function of fuel-air ratio and combustor design.

2. With combustor designs employing fuel injection upstream of the flame holder, the most pronounced effect of inlet-air temperature was found at lean fuel-air ratios; however, with internal injection the effect was greatest at rich fuel-air ratios. The region where the inlet-air temperature showed the greatest effect corresponded to the region of severe operating conditions, lean fuel-air ratios for upstream injection and rich fuel-air ratios for internal injection.

3. The use of a fuel-air mixing-control sleeve was found to be more beneficial at low inlet-air temperatures than at high temperatures with the can-type flame holder.

4. The performance of the sloping-baffle flame holder at an inlet-air temperature of 160° F with gasoline fuel was about the same as at 600° F with JP-4 fuel over a fuel-air ratio range from 0.020 to 0.062.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 31, 1953

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TABLE I. - SPECIFICATIONS AND ANALYSIS OF PRIMARY ENGINE FUELS

MIL-F-5624A GRADE JP-4 AND CLEAR GASOLINE

	Specifications, MIL-F-5624A	Analysis	
		MIL-F-5624A	Clear gasoline
A.S.T.M. distillation D 86-46, °F			
Initial boiling point		140	110
Percentage evaporated			
5		199	137
10	250 (max.)	224	154
20		250	178
30		270	200
40		290	218
50		305	235
60		325	250
70		352	265
80		384	284
90		427	305
Final boiling point	550 (max.)	487	358
Residue, percent	1.5 (max.)	1.2	1.3
Loss, percent	1.5 (max.)	0	1.4
Specific gravity	0.747 (min.), 0.826 (max.)	0.765	0.716
Reid vapor pressure, lb/sq in.	2.0 (min.), 3.0 (max.)	2.7	6.7
Hydrogen-carbon ratio		0.169	0.182
Net heat of combustion, Btu/lb	18,400 (min.)	18,700	18,925

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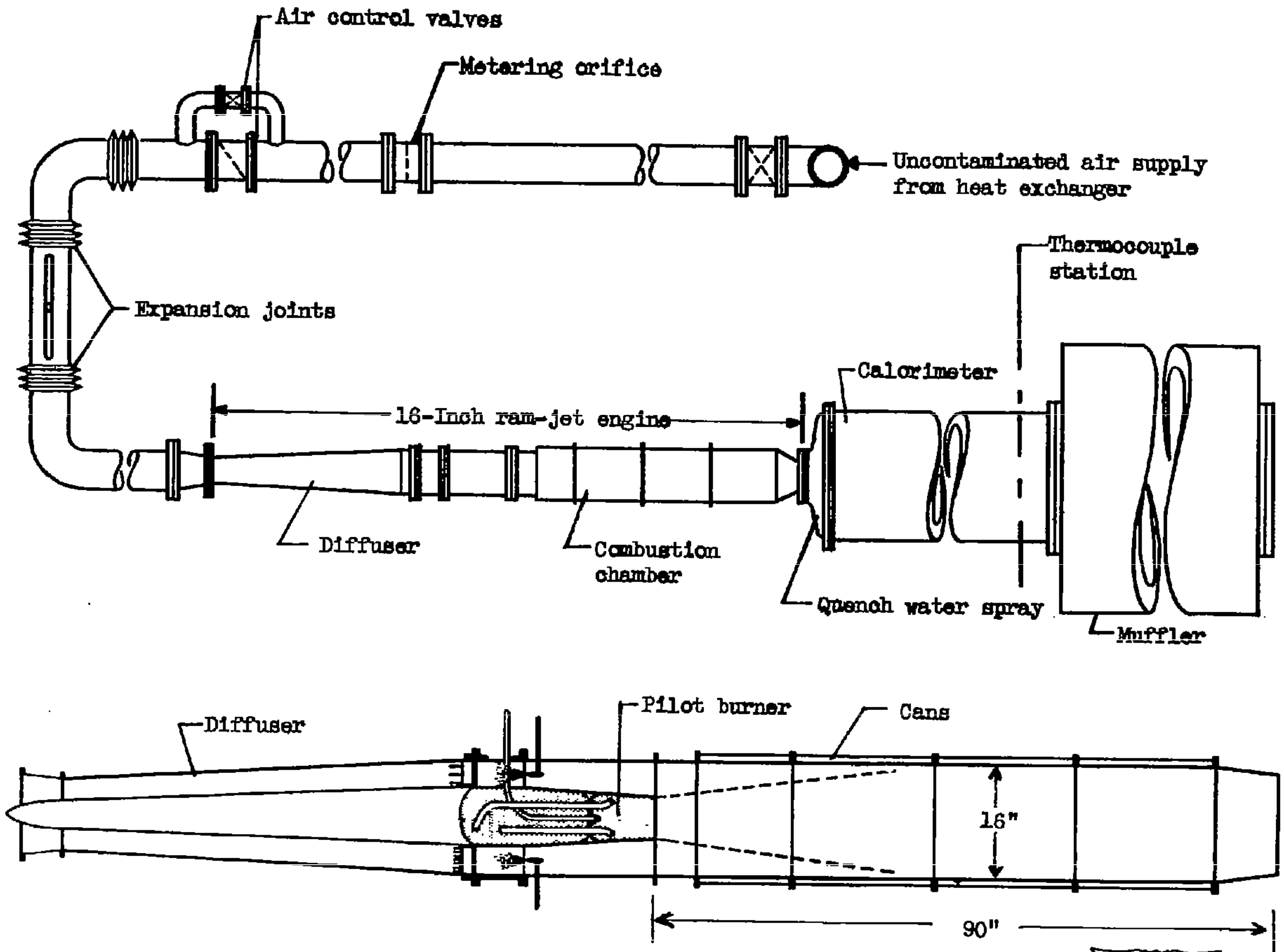

Figure 1. - Installation of 16-inch ram-jet engine.

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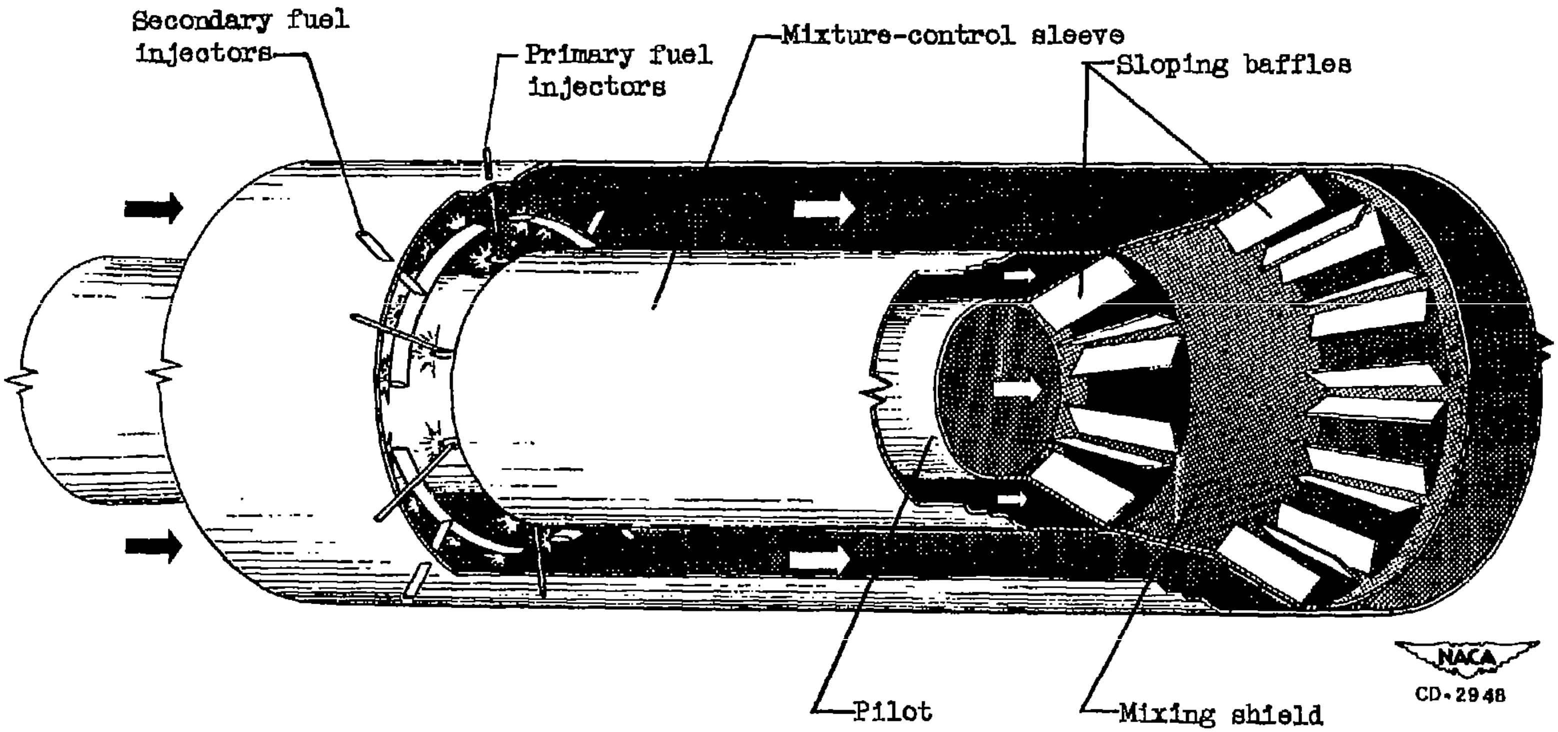
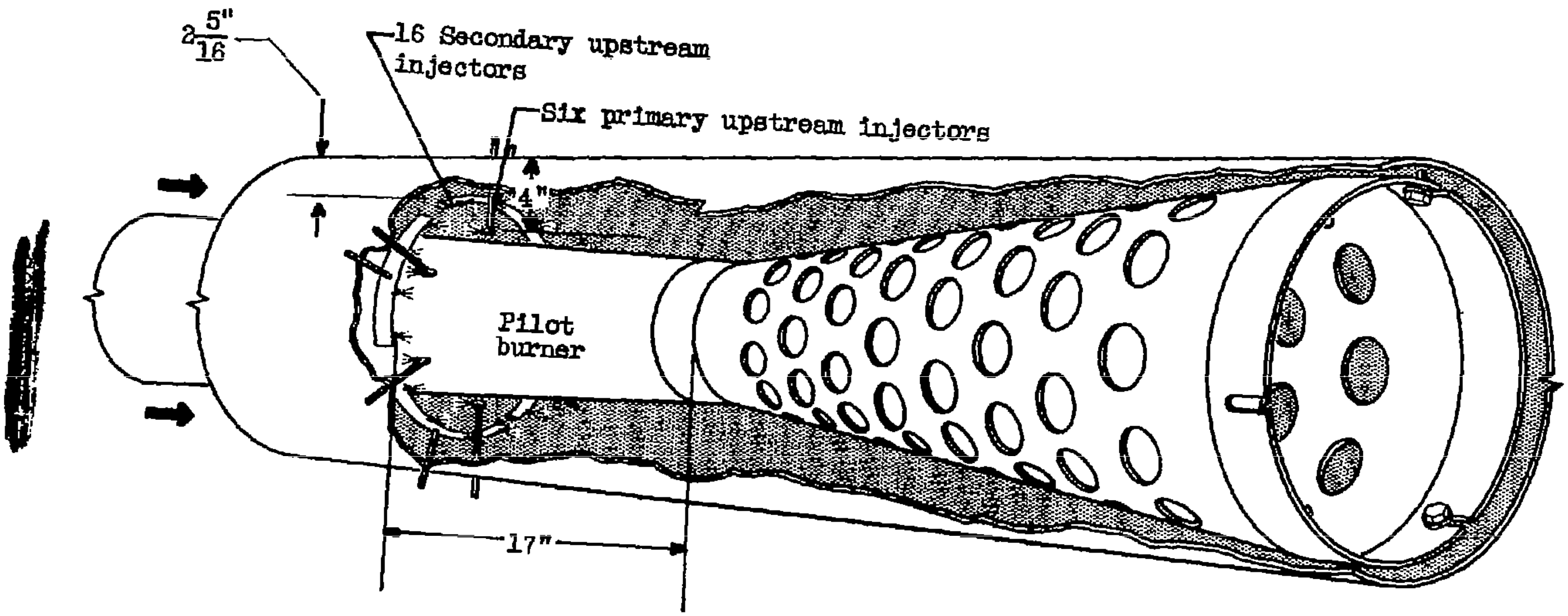


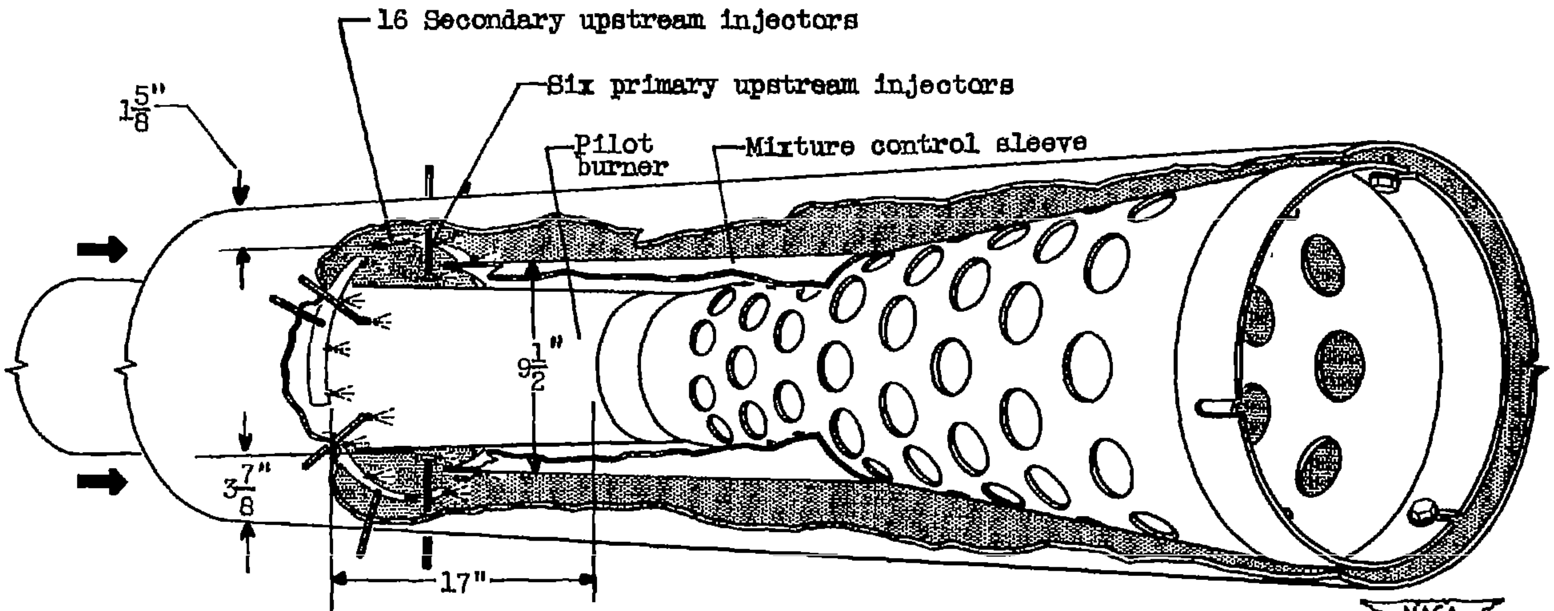
(a) Configuration A

Figure 2. - Combustor configurations.



(b) Configuration B.

Figure 2. - Continued. Combustor configurations.



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(c) Configuration C.

Figure 2. - Continued. Combustor configurations.

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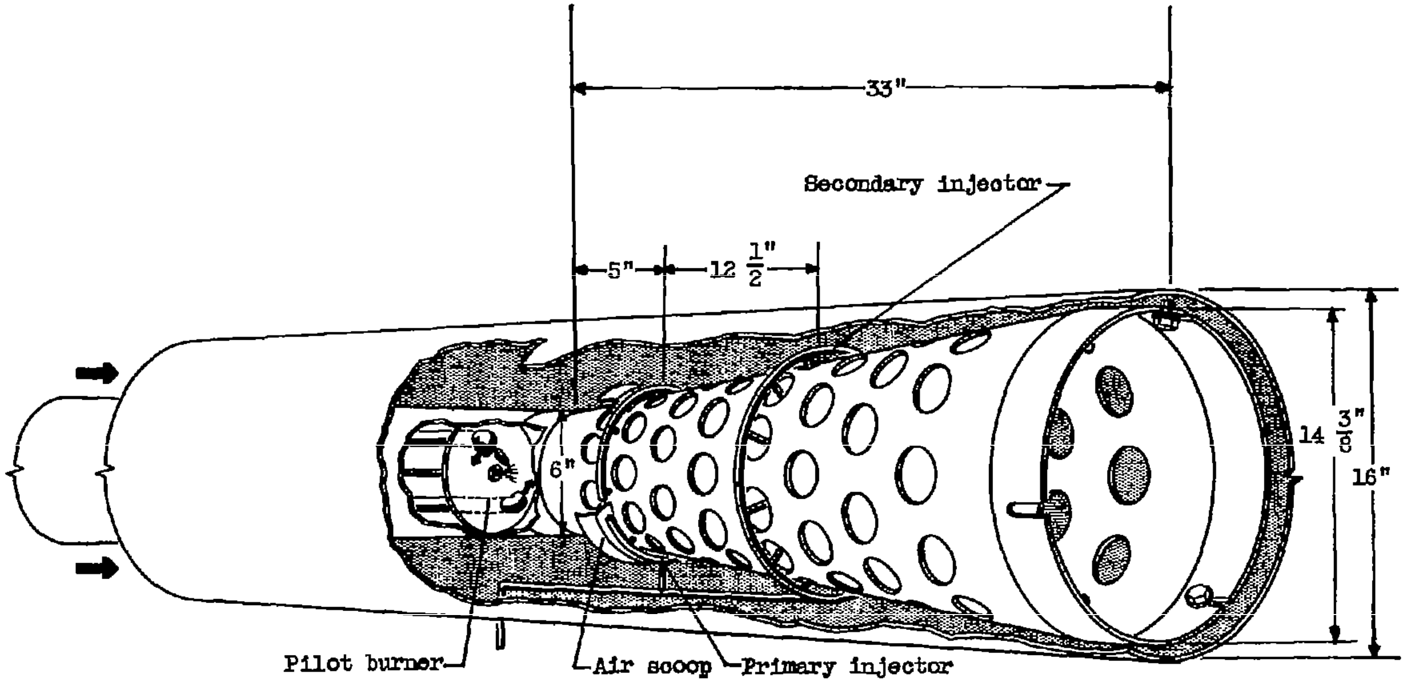

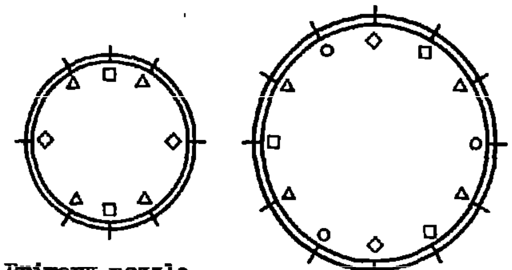

Primary nozzle arrangement

Secondary nozzle arrangement

Nozzle spray	Spray direction	Nozzle rating at 100 lb/sq in., gal/min: Primary manifold	Secondary manifold
○ Conical	Radial	0.667	1.000
□ Conical	45° Upstream		
◇ Conical	45° Downstream		
△ Flat	Downstream	.625	.625

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(d) Configuration D.

Figure 2. - Concluded. Combustor configurations.

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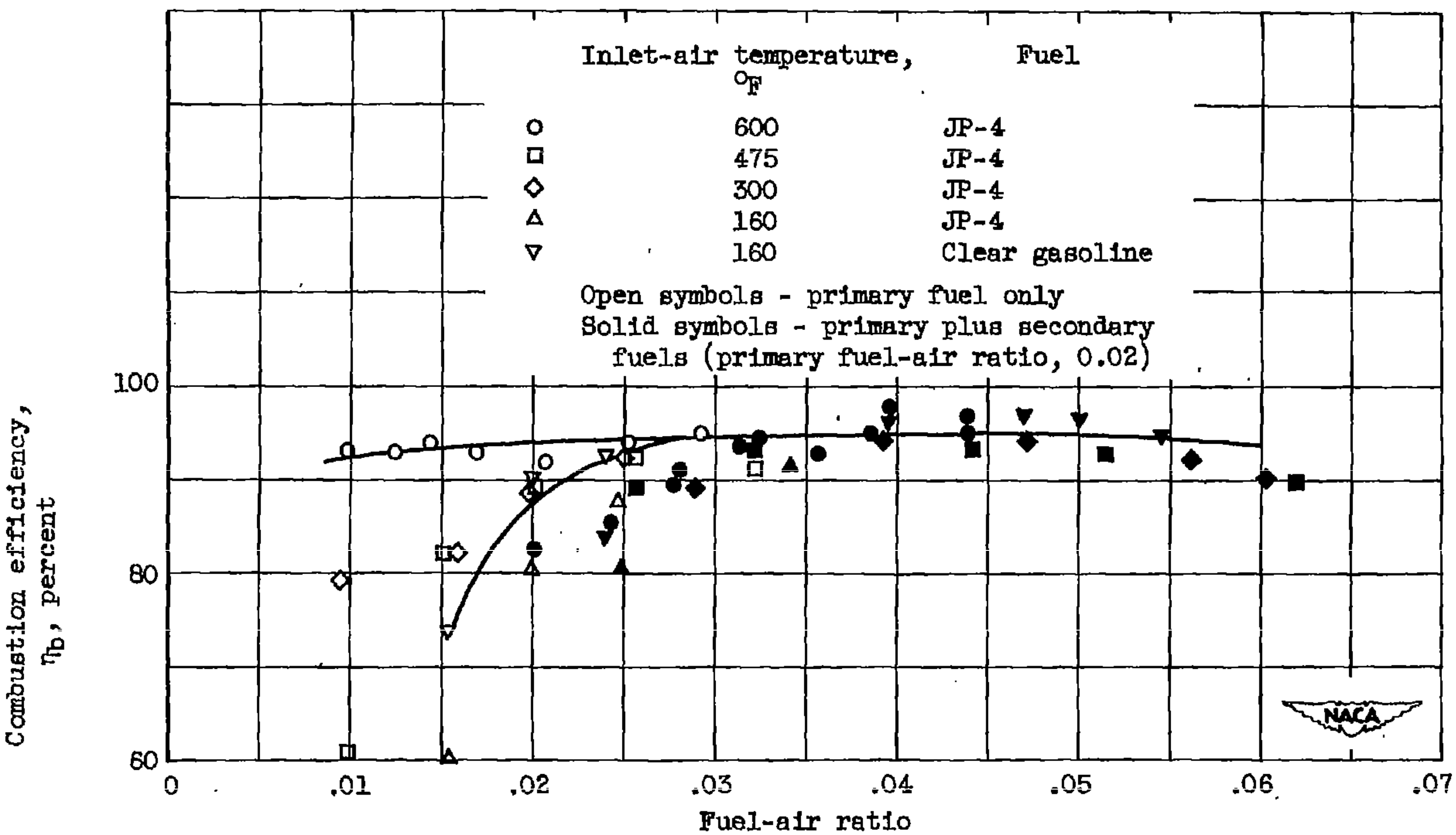

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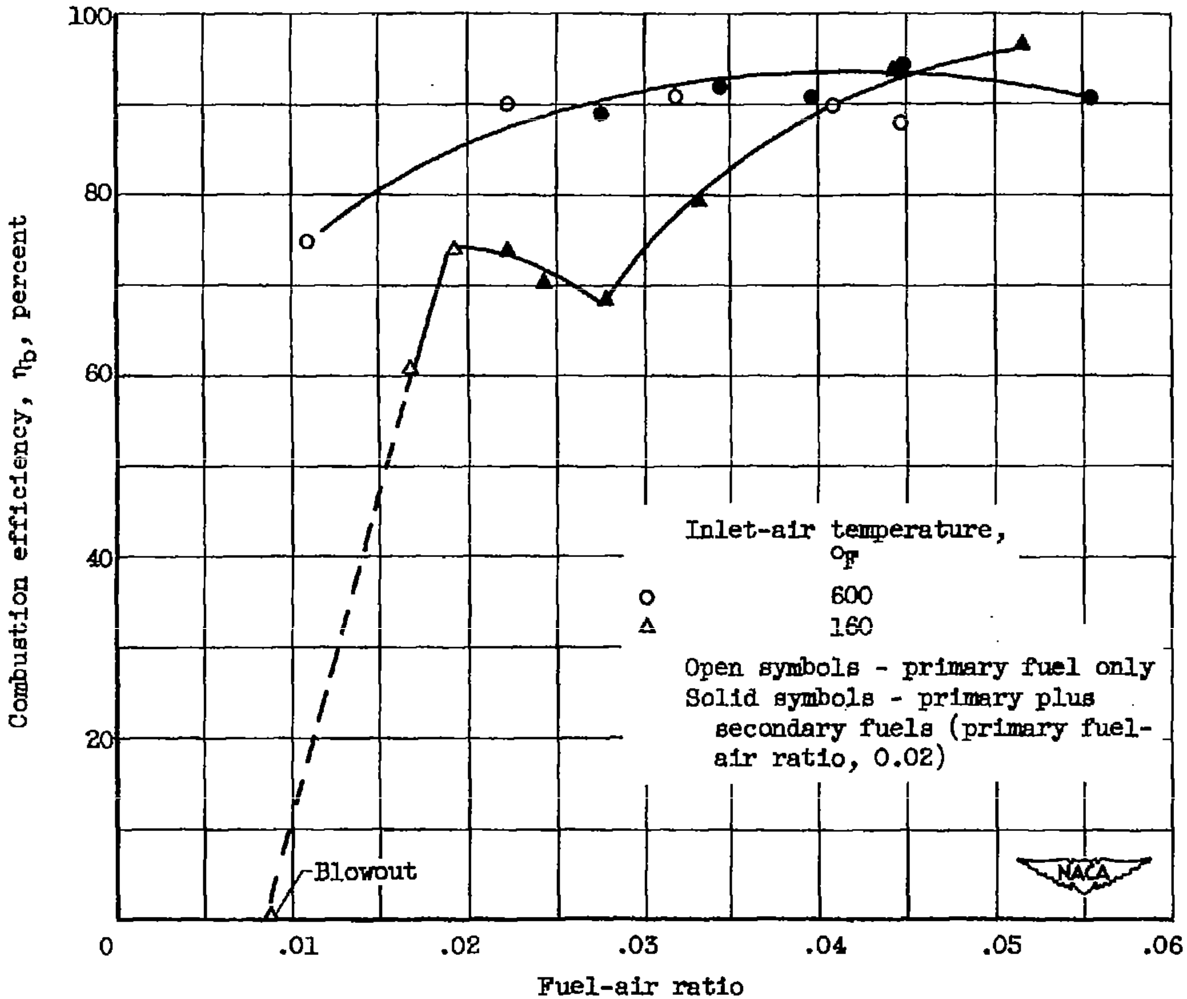
(a) Configuration A.

Figure 3. - Combustor performance of configurations A, B, and C over a range of inlet-air temperatures.



(b) Configuration B; JP-4 fuel.

Figure 3. - Continued. Combustor performance of configurations A, B, and C over a range of inlet-air temperatures.

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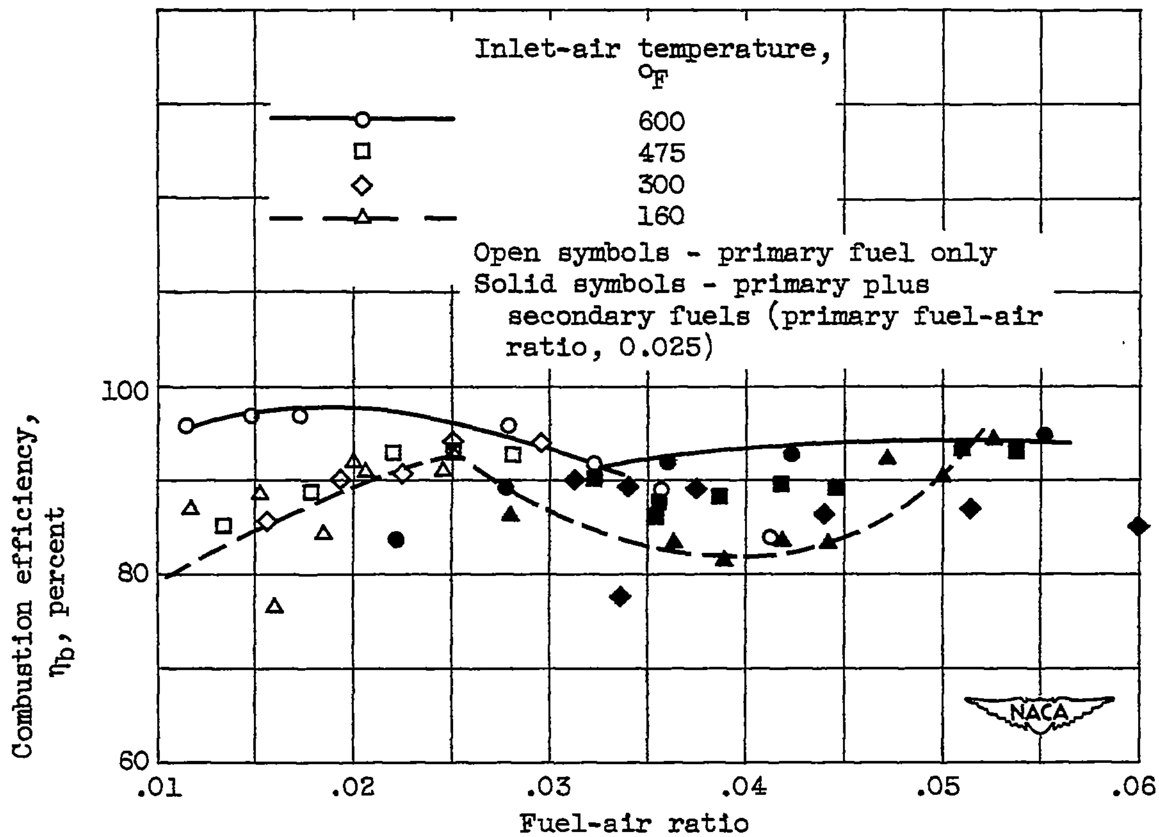

(c) Configuration C; JP-4 fuel.

Figure 3. - Concluded. Combustor performance of configurations A, B, and C over a range of inlet-air temperatures.

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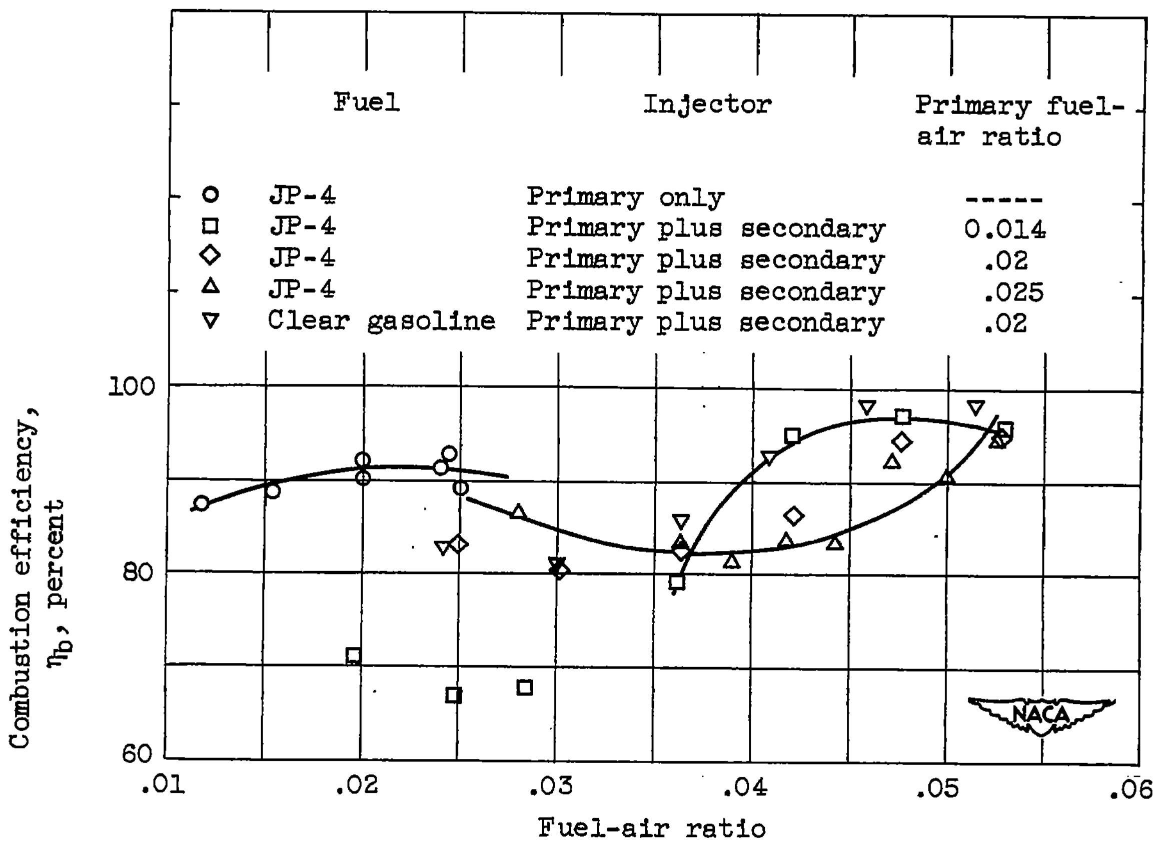

Figure 4. - Effect of primary fuel flow and fuel type on combustion with configuration C. Inlet-air temperature, 160° F; velocity, 165 to 260 feet per second; pressure, 54 to 33 inches of mercury absolute.

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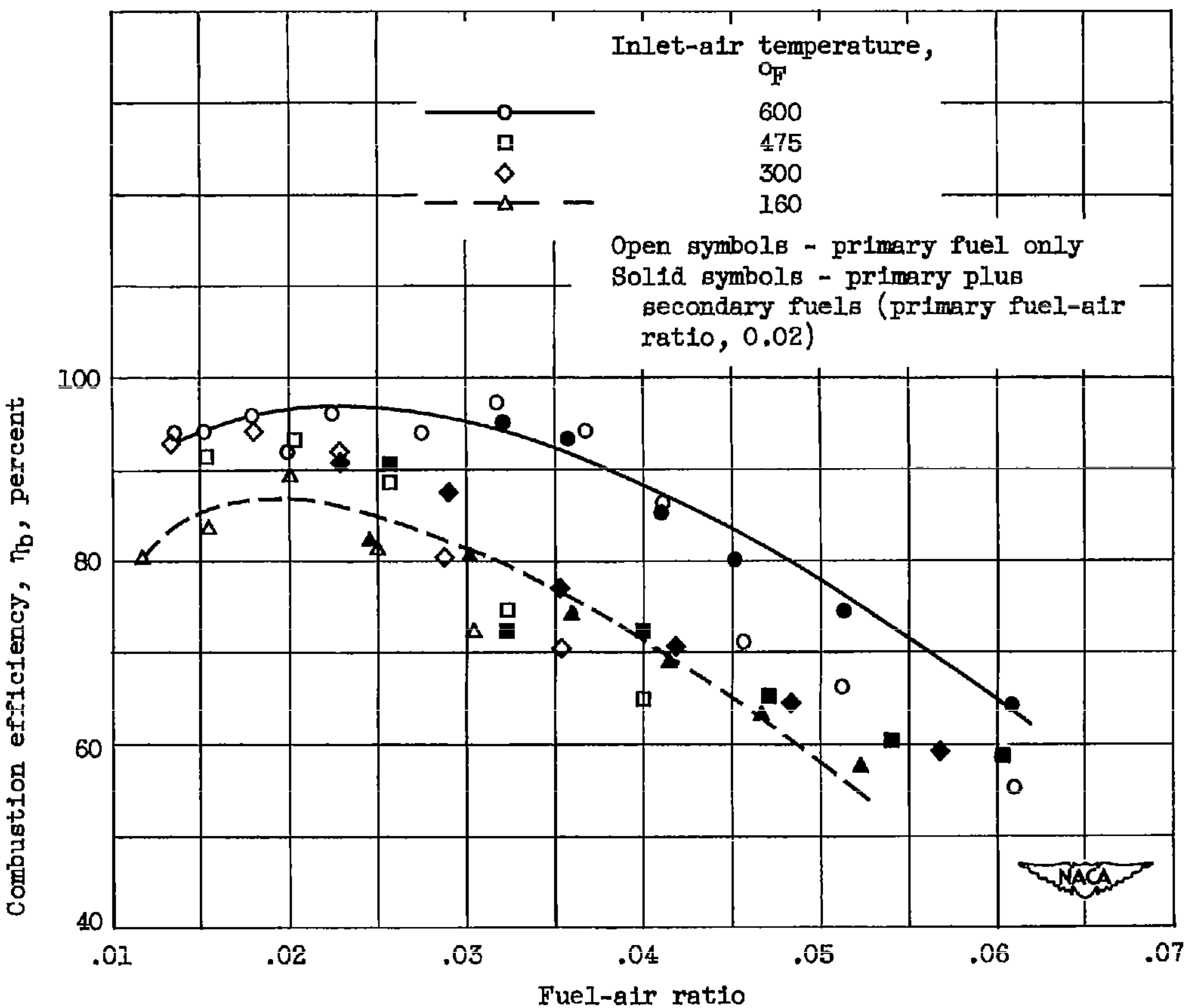

Figure 5. - Combustor performance of configuration D over a range of inlet-air temperatures. JP-4 fuel.

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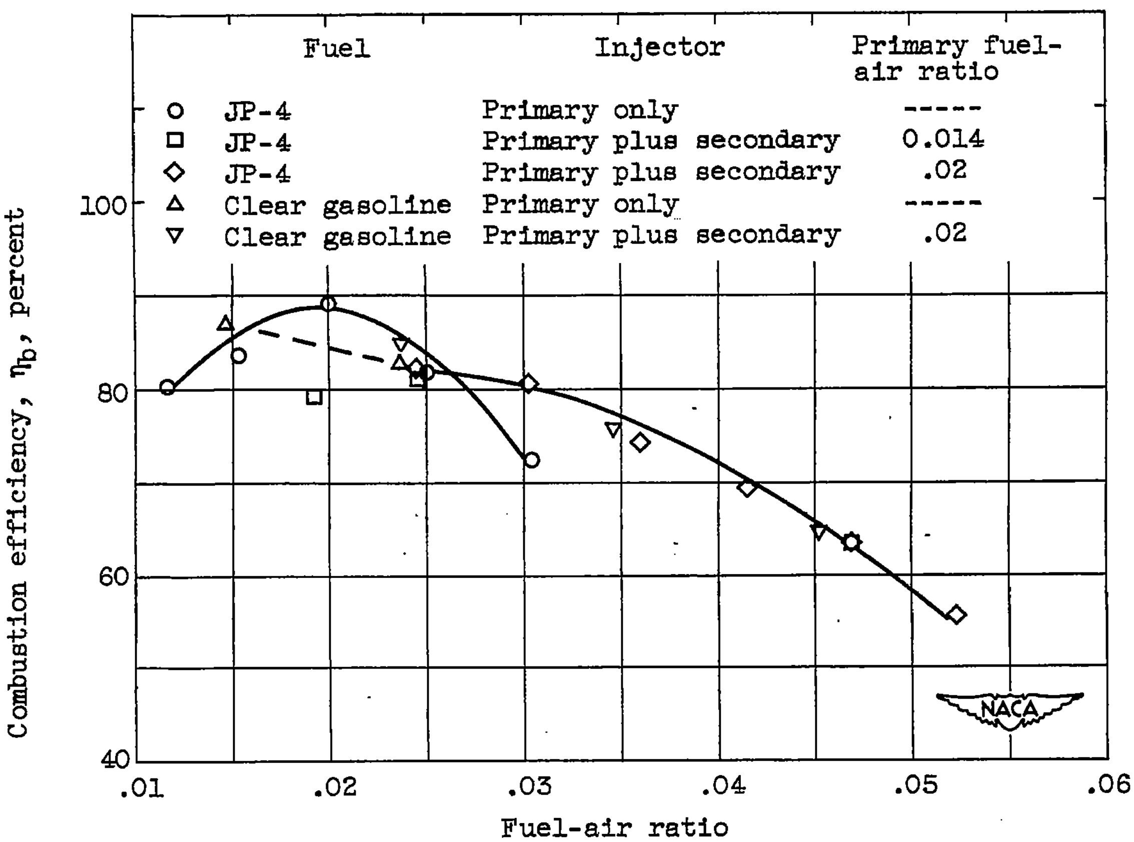

Figure 6. - Effect of primary fuel flow and fuel type on combustion with configuration D. Inlet-air temperature, 160° F; velocity, 165 to 260 feet per second; pressure, 54 to 33 inches of mercury absolute.

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